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QUANTIFICATION OF IMPACT DAMAGE IN CMC THERMAL PROTECTION SYSTEMS USING THIN-FILM PIEZOELECTRIC SENSORS (PREPRINT)

Samuel J. Kuhr and James L. Blackshire

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14. ABSTRACT
Thermal protection systems (TPS) are frequently subjected to impacts from micrometeoroids and ground handling during refurbishment. The damage resulting from such impacts can greatly reduce the vehicle's overall ability to resist extreme temperatures. Therefore, it is essential to have a reliable method to detect and quantify the damage resulting from impacts. In this effort, the effectiveness of lightweight thin film piezoelectric sensors was evaluated for impact detection and quantification in CMC wrapped TPS. The sensors, which were adhered to the bottom of the TPS tile, were used to sense impact events occurring on the top of the tile, with the ultimate goal of quantifying the level of impact level and damage state based on the sensed signals. A reasonable correlation between impact load levels and sensed response were observed for load levels between 0.07 – 1.00 Joules. An increase in signal frequency content was also observed as impact levels were increased, with specific frequency bands occurring in the 2 – 16 kHz range. A preliminary nondestructive evaluation of the impact damage sites was also accomplished, where a reasonable correlation between the gross damage features (i.e. impact crater dimensions) and signal response was observed.

15. SUBJECT TERMS
Thermal protection systems, ceramic matrix composite, thin-film sensors

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Quantification of impact damage in CMC thermal protection systems using thin-film piezoelectric sensors

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ABSTRACT

Thermal protection systems (TPS) are frequently subjected to impacts from micrometeoroids and ground handling during refurbishment. The damage resulting from such impacts can greatly reduce the vehicle's overall ability to resist extreme temperatures. Therefore, it is essential to have a reliable method to detect and quantify the damage resulting from impacts. In this effort, the effectiveness of lightweight thin film piezoelectric sensors was evaluated for impact detection and quantification in CMC wrapped TPS. The sensors, which were adhered to the bottom of the TPS tile, were used to sense impact events occurring on the top of the tile, with the ultimate goal of quantifying the level of impact level and damage state based on the sensed signals. A reasonable correlation between impact load levels and sensed response were observed for load levels between 0.07 – 1.00 Joules. An increase in signal frequency content was also observed as impact levels were increased, with specific frequency bands occurring in the 2 – 16 kHz range. A preliminary nondestructive evaluation of the impact damage sites was also accomplished, where a reasonable correlation between the gross damage features (i.e. impact crater dimensions) and signal response was observed.

Keywords: Thermal protection systems, ceramic matrix composite, thin-film sensors

1. INTRODUCTION

Thermal protection systems (TPS) are used in aerospace vehicles as a means of protecting metallic structural components from extreme temperatures (>2000°F). A typical TPS system is attached to the outer-skin of a structure, and is composed primarily of refractory materials which are lightweight and have excellent heat resistant properties. Amorphous ceramic glass, in particular, has found widespread use in TPS applications in the form of adhesively bonded porous foam blocks, glass coatings, and flexible blankets[1,2]. Because most ceramic and glass materials are brittle in nature, and have low fracture toughness, incidental damage occurring during launch, flight, or ground handling operations can result in the TPS material system becoming compromised, which can greatly reduce the vehicle's overall ability to resist extreme temperatures.

Previous research has shown that integrated sensor systems can be used to detect impact damage events in multi-layered composite and ceramic structures, which has tremendous payoff potential with regard to the flight safety and targeted maintenance of many aerospace systems[3-10]. In most cases, the detection of stress waves initiated by an impact have been the primary means of identifying when and where an impact event has occurred. The recent work of Kim[3], Pollock[4], and Sung[5], for example, have advanced impact sensing methodologies and signal analysis methods by parameterizing the acoustic response in terms of counts, peak amplitude, signal duration, energy, and frequency content via innovative MARSE (measured area in the rectified signal envelope), short-time Fourier transform (STFT), and wavelet transform (WT) analysis. The work of Smith[6], Bar[7] and Martin[8] are similarly of note with regard to the development and testing of novel, lightweight sensors for real-world applications. In addition to basic impact damage detection and localization, it would be very beneficial to quantify the damage state based on the received signals from the on-board sensing system. Some basic work has recently been done by Kim[3], Smith[6], and Bar[7] in an attempt to correlate damage state with detected signals for low-velocity impacts in composite laminates and graphite epoxy plates. This research showed that a potential correlation may exist between received signals and composite damage in the form of matrix cracks, delaminations, fiber breakage and fiber/matrix disbonding. However, the propagation of stress waves in the composite materials was complicated by anisotropic mechanical properties, stiffness variations, overlapping wave reflections, and the highly attenuative nature of the material as well as the part geometry, which all require further investigation and future research to better understand the correlation.

In this effort, we build on the research conducted by Kim[3] and Martin[8] to attempt to correlate received signals from thin-film polyvinylidene fluoride (PVDF) sensors with physical damage occurring in ceramic matrix composite (CMC) wrapped TPS material systems due to low-velocity impact events. The PVDF sensors were adhesively bonded to the bottom surface of a CMC-wrapped tile material system, which was subjected to low-velocity impacts on the top material surface. An attempt to develop an experimental methodology that would permit repeatable impact events was successfully accomplished. This allowed a reasonable correlation between damage state and received signals to be obtained multiple times in a repeatable fashion. The levels of impact were incrementally increased to provide a systematic depth penetration, with a special emphasis on the transition of damage state between the CMC-wrap material and the ceramic core foam material. A reasonable correlation was observed between increasing impact levels and the received PVDF sensor signals. An interesting trend in signal frequency response was also noticed that is being attributed to the occurrence of different damage modes as load levels were increased. A preliminary nondestructive evaluation of gross damage features was also accomplished which correlated well with observed PVDF signal levels.

2. EXPERIMENT

2.1 CMC-Wrapped Tile TPS Materials

A schematic of a ceramic matrix composite (CMC) wrapped-tile and its individual components are displayed in Figure 1. The tile consists of a foam core material surrounded by a more durable CMC wrap material which is attached to the core on five of its six sides. The wrap layer is approximately 1 mm thick and consists of woven ceramic fibers which are infiltrated with a ceramic matrix material. The core material is made up of a light weight, porous ceramic foam of ~150 x 150 x 50 mm in dimensions. The density of the foam and wrapped CMC composite material were 0.152, and 0.281 gm/cm^3, respectively.

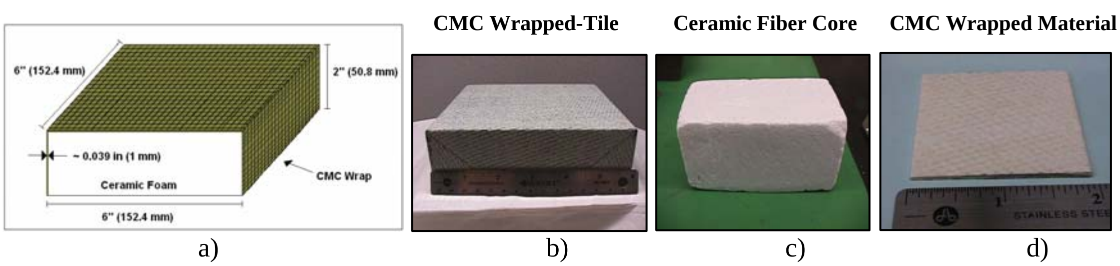
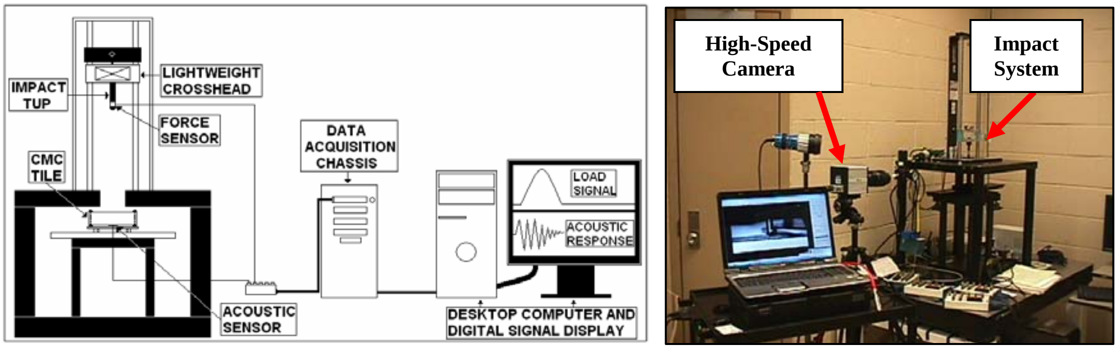


Fig. 1. a) Schematic of CMC-wrapped tile. Digital images of b) actual CMC wrapped tile, c) ceramic foam core material, and d) CMC-wrap material.

2.2 Low-Velocity Impact System

Figure 2 displays a schematic and digital picture of the Instron Dynatup impact tester and data acquisition hardware. The tester is equipped with a lightweight composite crosshead which is fitted with a 10 cm long impact 'tup' assembly. The tup assembly is instrumented with a force sensor (PCB, 208M136) and a hemispherical steel insert 10 mm in diameter. The impact system provides a calibrated load level for each impact event by tracking the drop velocity and loadcell response for each event. This provides a means for modeling the impact physics and material damage response if desired. Signals generated from the tup force and PVDF sensors were simultaneously recorded using a National Instruments (NI) chassis (NI PXI-1042) and a four channel data acquisition card (NI PXI-6115) which had a maximum sampling rate of 10MS/s. Data acquisition was controlled by a Labview based program and was triggered off of the force sensor and predetermined voltage threshold. A high-speed camera system (Motion Engineering FASTCAM 1024 PCI) was also used to provide a high speed recording of the impact events.



a) b)

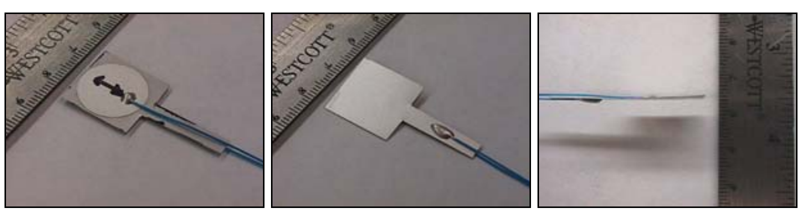
Fig. 2. a) Schematic of Instron Dynatup impact tester and National Instrument data acquisition system, and b) image of impact system along with high-speed camera system.

2.3 Polyvinylidene Fluoride (PVDF) Sensors

The PVDF sensors used in this study were fabricated from polyvinylidene fluoride sensor sheet material manufactured by Measurement Specialties, Inc. Important material properties for the PVDF are provided in Table 1[11-15]. Circular PVDF sensors were prepared from the received 279 mm (11 inch) x 203 mm (8 inch) x 110 µm film sheet by acetone etching and cutting of the sheet material to the desired sensor size (16.3 mm x 19 mm x 110 µm; Wt: 0.32 gms). Figure 3 depicts a typical sensor. Electrical leads were attached to the PVDF sensor using a room temperature conductive silver epoxy. In attempt to reduce the signal complexity and appropriately match the impedances of the sensors to that of the data acquisition hardware, the impact responses of the sensors were recorded without amplification.

Table 1. Properties of PVDF sensors

Manufactured by:	Measurement Specialties, Inc. (MSI)
Resonant Frequency	10 MHz, 6.8 MHz
Enclosed in a casing	No
Damping material around sensing element	No
Young's Modulus (GPa)	2-4
d_{33} (10^{-12} C/N or 10^{-12} m/V)	-33
g_{33} (10^{-3} Vm/N)	-339
Weight (gm)	0.32
Shape	Disc
Dimensions (mm)	dia = 16.4 mm, ht = 0.0001 mm



a) b) c)

Fig 3. Digital images of polyvinylidene fluoride sensors: a) top view, b) bottom view, and c) side profile.

High sensitivity to the impact phenomena is required for an effective measurement of the damage. PVDF is a semi-crystalline polymer which has a sensitivity of ~339 x 10^{-3} Vm/N, which makes it an ideal sensor for receiving stress wave signals due to impact events[7]. Additionally, the outer uncoated film area acts as a ground[6]. PVDF has a heightened sensitivity to in-plane displacements when adhesively bonded to structures and has high internal damping which reduces transducer ringing and flattens its frequency response[13].

2.4 Low-Velocity Impact Testing and Analysis

A series of impact events were accomplished at five drop heights ranging from 1 inch to 13 inches, which correspond to impact energy levels of 0.768 – 0.9980 Joules (Table 2). For each impact event, a single PVDF sensor was adhesively bonded to the bottom of the TPS material directly under the impact site on the top of the material. A standardized procedure was established and used to validate that the bonded sensor and material system were ready for the low-velocity impact event. This standardized procedure involved a series of repetitive tap-tests (1mm drop height where no damage to the TPS material surface occurred) that provided a reference signal for the tup loadcell and the PVDF signals which could be compared to previously acquired reference signals. If a deviation from the reference signal was noticed, the measurement was abandoned and a different location on the material surface was chosen and/or the sensor was re-bonded. This provided a means for acquiring reproducible low-velocity impact measurements which could be compared to one another for statistical significance if desired. Once the tap-test was successfully accomplished, a low-velocity impact was conducted where permanent damage to the TPS material was anticipated.

For the low-velocity impact tests, the PVDF and tup loadcell signals were automatically recorded (time –vs- voltage response) along with a high-speed camera recording of the impact event. Following the capture of each data set, a standard signal analysis of the time, phase, and amplitude information was accomplished along with a basic assessment of frequency content using a fast Fourier transform. For every impact event a new location on the TPS sample surface was chosen, where care was taken to keep the impact locations near the center of the sample (to minimize any potential edge effects), and to keep subsequent impacts away from previous impact locations (~1” separation). A preliminary gross damage assessment was also accomplished after each impact using digital microscopy, which provided damage depth, area, and volume characteristics of the impact sites.

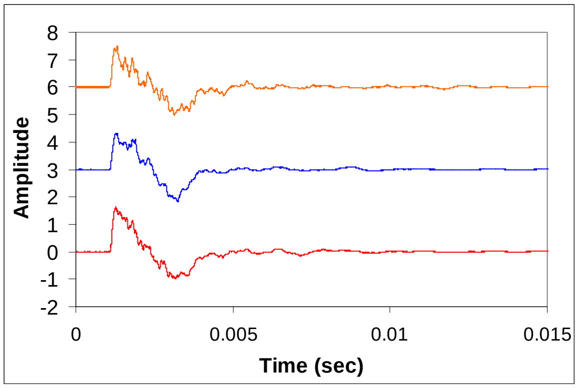
Table 2. Summary of Impact Energies Performed on CMC Tile

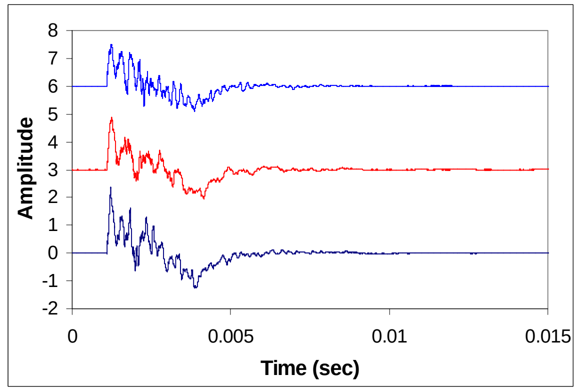
Drop Height	Impact Energy
25.4 mm (1 inch)	0.0768 J
76.2 mm (3 inch)	0.2303 J
127.0 mm (5 inch)	0.3838 J
177.8 mm (7 inch)	0.5374 J
330.2 mm (13 inch)	0.9980 J

3. RESULTS AND DISCUSSION

3.1 PVDF Signal Responses for Increasing Drop Heights

Figure 4 displays the PVDF signal responses for the 1”, 3”, 5”, and 7” impact events. A set of three offset signals is displayed in each graph, corresponding to three individual impact hits for each drop height condition. The PVDF sensors generated peak-to-peak voltage levels between 2 Vpp – 5 Vpp for the four impact heights depicted in Figure 4, with a maximum peak voltage of ~ 9 Vpp for the 13 inch drop height condition (shown in Figure 5). A representative signal for each of the five drop heights is provided in Figure 5a, along with a plot of the average PVDF signal levels vs impact drop height (Figure 5b), where an average and standard deviation spread bar is depicted for each drop height case. An increase in the PVDF signal response was observed as the drop height was increased.





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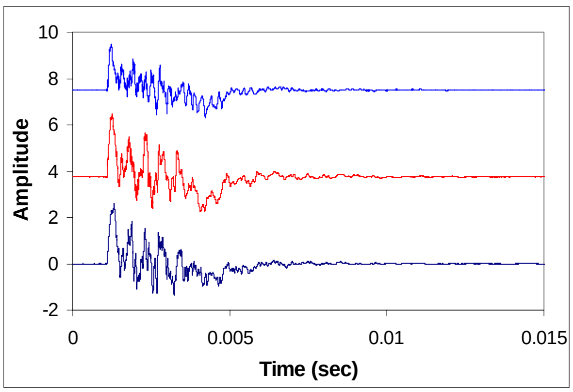
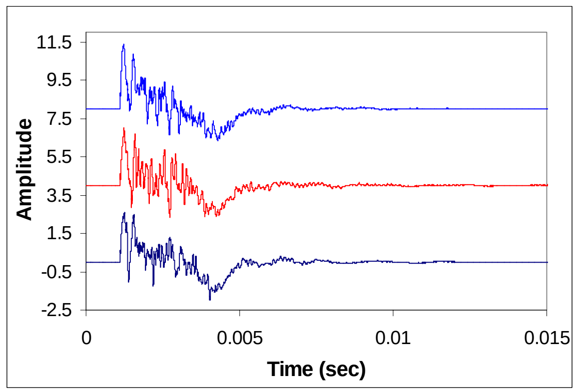
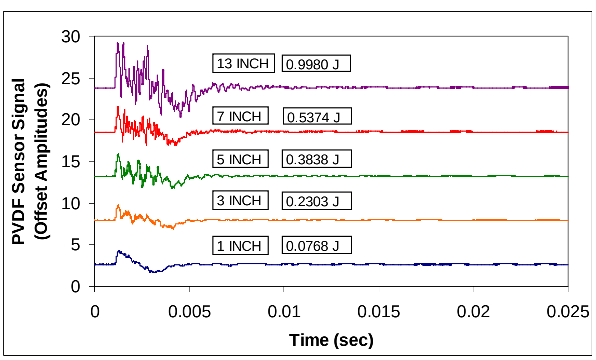
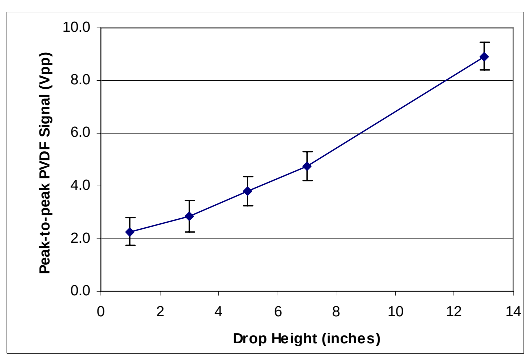




c) d)

Fig. 4. PVDF signal responses for impact heights of: a) 1 inch, b) 3 inch, c) 5 inch, and d) 7 inch.



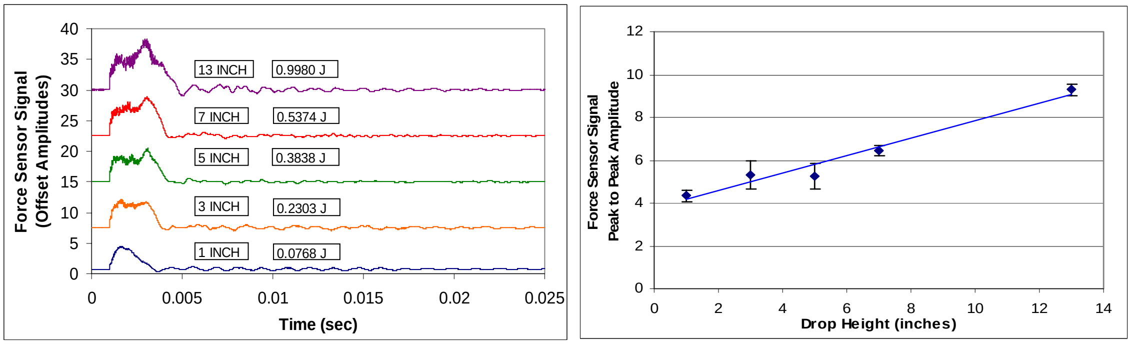


a) b)

Fig. 5. a) Representative PVDF signal responses for 1”-13” impact heights, and b) plot of PVDF signal response versus drop height.

3.2 Comparison of ‘tup’ Loadcell Responses and PVDF Signal Responses

As mentioned in Section 2, the low velocity impact system has an integrated loadcell that provides an independent measure of impact force as a function of time for each impact event. Similar to the PVDF sensor, which was placed on the bottom of the TPS tile, the loadcell provides piezoelectric sensing information regarding the time-history of loading events and damage evolution within the TPS material as the impact head makes contact with, and penetrates into, the TPS material system. Figure 6a provides a comparison of representative loadcell responses for each of the five drop heights, while Figure 6b depicts the loadcell signal level vs impact drop height, where an average and standard deviation spread bar is depicted for each drop height case. A reasonable trend between the drop height and the loadcell signal response was observed.



a) b)

Fig. 6. a) Representative loadcell signal responses for 1”-13” impact heights, and b) plot of drop height versus loadcell signal response.

A comparison of the signal response characteristics of the PVDF sensors placed on the bottom of the TPS material and the loadcell signal responses for the impact tup is depicted in Figure 7. The data in Figure 7 corresponds to the average PVDF and loadcell responses for multiple hits along with standard deviation spread bars. A zero-point condition for each case was also included in the plot. A very good reproducibility was noticed in the data based on the standard deviation spread bars, with a general quadratic increase in the signal response characteristics between the two signal types.

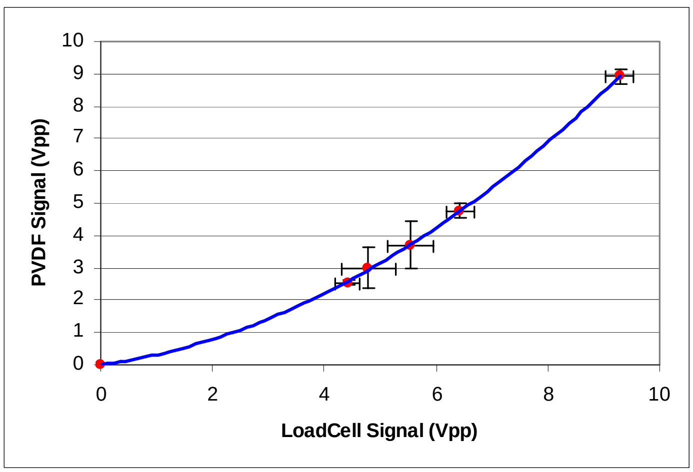


Fig. 7. Plot of loadcell signal response (Vpp) and corresponding PVDF signal response for low-velocity impacts between 1” and 13” drop heights (0.0768J – 0.998J).

3.3 PVDF Signal Frequency Analysis

Figure 8 displays representative PVDF signals and corresponding frequency spectra obtained using fast Fourier transform (FFT) analysis for each drop height from 1” to 13”. The frequency content of the 1-inch drop height corresponded to a maximum frequency spike near 30 Hz with additional frequencies existing out to 4 kHz, with dramatic increases in frequency content observed between 2 kHz and 12 kHz as the drop height was increased systematically to 13 inches drop height.

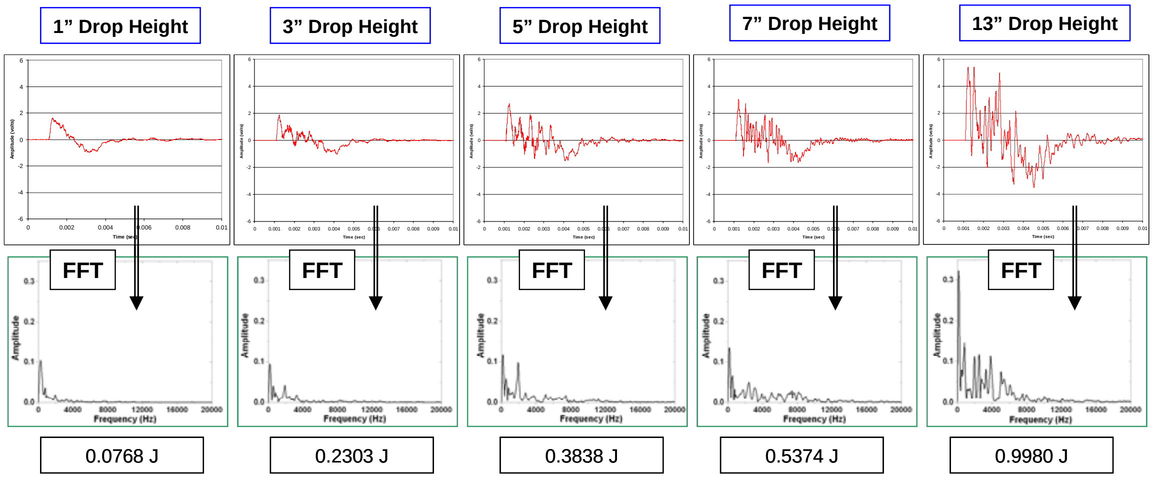


Fig. 8. PVDF signals and corresponding FFT frequency spectrum analysis for 1” to 13” drop heights.

3.4 Impact Damage Assessment

Optical microscope images were obtained for each impact site, where a rough nondestructive assessment of impact crater area, depth, and volume were obtained using a calibrated Nikon optical microscope. Figures 9a-f depict representative digital images for the non-damaged, 1”, 3”, 5”, 7”, and 13” drop heights, respectively. From the initial visual inspection, the impact energy of 0.0768 J (1” drop height) shown in Figure 9b did not produce discernible damage to the surface of the CMC wrap. However, after further examination under the optical microscope, the impact crater was identified and its parameters were measured. Increasing the impact energy to 0.2303 J (3” drop height shown in Figure 9c) resulted in a more significant compression of the CMC surface, but complete penetration through the wrap material was not achieved. The remaining impact energies demonstrated penetration through the CMC wrap.

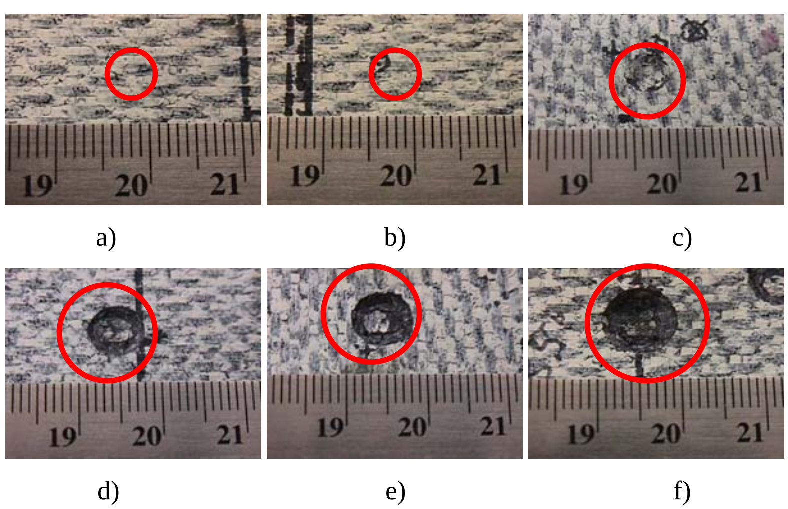
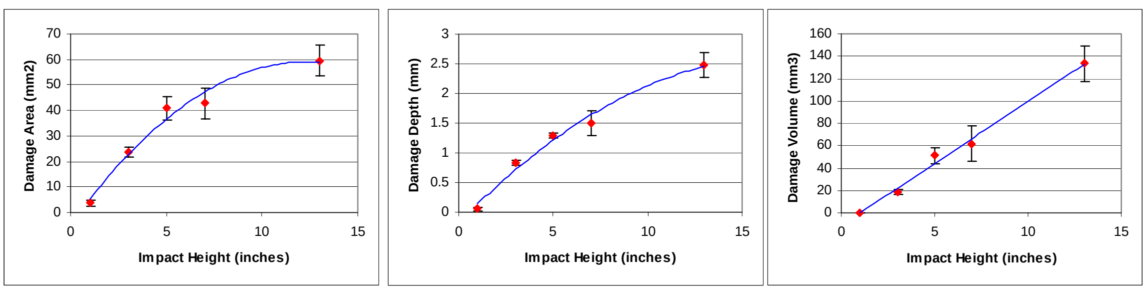


Fig. 9. Digital images of the a) undamaged, b) 1-inch, c) 3-inch, d) 5-inch, e) 7-inch, and f) 13-inch cases.

Table 3 provides the measurement results for the average area, depth, and volume of the damage sites for the 1” – 13” drop height conditions. The volume of damage incurring from impact was approximated under the assumption that the damage zone in each case maintained its hemispherical geometry (from the impacting tup). Figure 10 displays a series of plots corresponding to the measured damage levels for increasing impact drop height for damage area, depth, and volume, respectively. The damage area and depth plots show a general increase in damage level as the impact level is increased with a saturation or plateau effect at higher impact energies, while the volume measurements show a general linear trend. The area damage saturation is likely due to the fixed size of the impact head, which would tend to place a limit on the damage area at higher impact levels. It should also be noted that the CMC wrap thickness was approximately 1 mm in thickness, where the damage mechanisms are more likely to involve multiple material layers of the overall CMC wrapped tile as the impact level increases. Further studies are underway to evaluate these effects in more detail.

Table 3. Damage assessment values corresponding to impact area, depth, and volume.

Impact Energy (J)	Surface Area (mm2)	Impact Depth (mm)	Volume (mm3)
0.0768	3.757	0.052	0.200
0.2303	23.534	0.832	19.088
0.3838	40.837	1.301	51.138
0.5374	42.843	1.497	61.737
0.9980	59.48	2.478	133.33

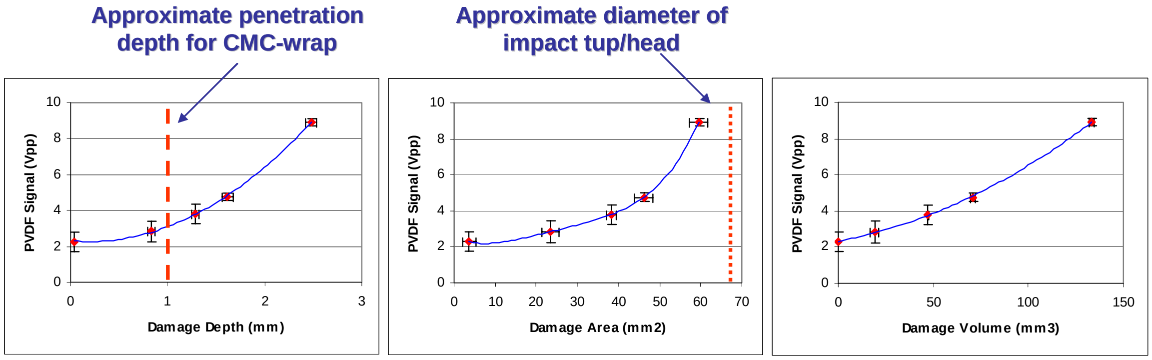


a) b) c)

Fig. 10. Average damage levels for increasing drop-heights, a) area, b) depth, and c) volume.

3.5 PVDF Sensor Signals vs Impact Damage Levels

The primary goal of this research effort was to attempt to correlate physical damage state occurring in CMC-wrapped tile TPS systems due to impact events with integrated thin-film sensing responses. As shown in Figures 4, 5, and 8, the sensing of stress waves with PVDF thin-film sensors offers a reasonable solution for detecting impact damage events with good sensitivity. The general characteristics of the PVDF stress-wave signals show a compact time-signature response with a duration of ~5 milliseconds. This compact time-signature feature, along with the relatively simple waveform characteristics (see Figure 8), provide an opportunity for damage characterization based on simple PVDF signals and analysis methods. An example of this is depicted in Figure 11, where the peak-to-peak signal response of the PVDF sensors are plotted relative to the measured damage levels for low-velocity impacts between 1” – 13” drop heights. Although a linear relationship between PVDF signal response and damage levels does not appear to exist, a quadratic relationship does appear to exist between the PVDF signals and damage area, depth, and volume. In addition, a good reproducibility of sensor response and damage level was observed for multiple impact events at different locations on the CMC-wrapped tile surface. Additional efforts are underway to understand the correlation of specific damage features (fiber breakage, matrix cracking, disbonding) with PVDF signal responses.



a) b) c)

Fig. 11. PVDF signals vs measured damage levels, a) damage depth, b) damage area, c) damage volume.

4. CONCLUSIONS

Previous research has shown that integrated sensor systems can be used to detect impact damage events in multi-layered composite and ceramic structures, which has tremendous payoff potential with regard to the flight safety and targeted maintenance of many aerospace systems. In this effort, the effectiveness of lightweight thin film piezoelectric sensors was evaluated for impact detection and quantification in a CMC wrapped TPS material system. The sensors, which were adhered to the bottom of the TPS tile, were used to sense impact events occurring on the top of the tile, with the ultimate goal of quantifying the level of impact level and damage state based on the sensed signals. A reasonable correlation between impact damage levels and sensed PVDF response was observed for load levels between 0.07 – 1.00 Joules, with an apparent quadratic relationship between gross damage features and peak-to-peak signal levels. An increase in signal frequency content was also observed as impact levels were increased, with noticeable frequency bands being generated in the 2 – 16 kHz range as impact levels were increased. A systematic testing methodology was also developed, which permitted repeated impact testing and reproducible results to be obtained. Additional work is planned to understand the detailed damage occurring due to impact events in these complex material systems, and to develop and use integrated sensor systems to evaluate the TPS system performance capability levels.

5. ACKNOWLEDGEMENTS

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